Requirements for Next Generation Comprehensive Analysis of Rotorcraft

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Abstract

The unique demands of rotorcraft aeromechanics analysis have led to the development of software tools that are described as comprehensive analyses. The next generation of rotorcraft comprehensive analyses will be driven and enabled by the tremendous capabilities of high performance computing, particularly modular and scaleable software executed on multiple cores. Development of a comprehensive analysis based on high performance computing both demands and permits a new analysis architecture. This paper describes a vision of the requirements for this next generation of comprehensive analyses of rotorcraft. The requirements are described and substantiated for what must be included and justification provided for what should be excluded. With this guide, a path to the next generation code can be found.

INTRODUCTION·

The unique demands of rotorcraft aeromechanics analysis have led to the development of software tools that are described as comprehensive analyses. The word "comprehensive" refers to the need to perform with a single tool all computations, for all operating conditions and all rotorcraft configurations, as required at all stages of the design process. Because of the special nature of rotor phenomenon, particularly the impact of rotation on the aerodynamics and structural dynamics of the rotor blades and the resulting interactions between components and between disciplines, the development of the needed software must be led by the rotorcraft community.

The next generation of rotorcraft comprehensive analyses will be driven and enabled by the tremendous capabilities of high performance computing (HPC). Computer

hardware advances of the last twenty years have greatly increased the productivity of rotorcraft analyses, or permitted attacks on ever larger problems. Yet the codes of the current generation were designed for a single processor. Effective application of computational fluid dynamics to rotor problems is only possible with multiple cores. By using 100's of cores, RANS calculations for the rotor and even the entire helicopter are currently possible in the research environment. By using just 10's of cores, CFD today can be used in the design environment for key problems. Extensive research is now focused on the coupling between the CFD aerodynamics and simple rotor structural dynamics, including investigations of algorithmic and implementation issues. But all of the current efforts fall well short of deserving the appellation "comprehensive".

Numerous correlation studies highlight the need for progress in the prediction of rotorcraft characteristics. Excellent assessments of the state-of-the-art of rotorcraft tools are presented in References 1 to 3. A simplified view is given in Table 1, which shows the goal for

predictive capability and estimates of current capabilities using engineering tools (comprehensive analyses) and physics-based models (such as RANS coupled with a comprehensive analysis for trim and structural dynamics). The percentages given are accuracy of calculations compared to measured values, based on full amplitude of the measured data. Note that in most cases the goal is an order of magnitude improvement over current capabilities. An overall metric for progress at program level is a factor of 10 improvement in accuracy of design and analysis capability at the end of 15 years. This metric can also be characterized as a factor of 2 improvement in prediction accuracy every 4.5 years. In order to achieve such a goal in the engineering environment, it will be necessary to improve throughput of computations by many orders of magnitude.

Table 1: Estimate of Predictive Capability for State-of-the-Art Rotorcraft Tools

	Goal	Engineering Tool	Physics-Based Model
Forward flight performance	1%	4%	20%
Hover performance	0.5%	2%	2% (but flow-field not correct)
Airloads (c_n/c_m), without mean	1%	10% / 35%	6% / 20%
Airloads (c_n/c_m), with mean	1%	10% / 35%	15% / 40%
Blade loads (flap / chord / torsion)	3%	20 / 35 / 25%	20 / 35 / 25%
Vibration	10%	100%	Not available
Stability (fraction critical damping)	0.002	0.02	Not available
Noise	3 dB	10 dB	15 dB

There is no question that a new generation of comprehensive analyses is required. While recognizing the tremendous advances of the last few years, the current capability to analyze rotorcraft must still be considered unsatisfactory, deficient in both accuracy and productivity. Development of a comprehensive analysis based on high performance computing both demands and permits a new analysis architecture. This paper describes the requirements for this next generation of comprehensive analyses of rotorcraft. The intent is to provide the foundation for planning software development projects, so it is important that the requirements cover both what must be included and what should be excluded. The time frame of the proposed development projects is implementation within 5 years, and an expected 20-30 years of useful application and continued development.

COMPREHENSIVE ANALYSES

A comprehensive analysis for rotorcraft must perform with a single code calculations of performance, blade loads, vibration, airframe and drive train loads, aeroelastic stability, flight dynamics and handling qualities, and noise. All of these tasks demand high fidelity aeromechanics models for accurate results. Because these tasks require a similar level of technology and similar models, they must be performed with a single tool. The history of development of computer programs for rotorcraft started with the alternative approach of developing multiple codes separately for several disciplines, such as performance, dynamics, and handling qualities. This experience with first generation codes provided solid evidence of the resulting inefficient use of development and application resources, and inevitable disparity of treatment of the various problems.

The word "comprehensive" also refers to the capability to analyze all operating conditions, including hover and level flight, steady (climb, descent, and turns) and maneuvering flight. Routine calculation of loads in maneuvers is essential for effective design capability. The word also refers to the multi-disciplinary nature of rotorcraft phenomenon. For the current codes, "comprehensive" also means the ability to handle all rotorcraft configurations, with arbitrary geometry, including novel and advanced designs. A comprehensive analysis for rotorcraft must be able to model all rotorcraft configurations: conventional, including main rotor and tail rotor, tandem, coaxial, and tiltrotor; common configurations such as compound helicopter, tilt wing, tip drive, and tail booms; and arbitrary configurations, including wings and propellers. All rotor types and arbitrary geometry must be modelled — whatever the designers can invent. A major limitation of first generation tools was the restriction to specific configurations and rotor types. It is necessary to analyze the full aircraft in free flight, for even when the focus is on a single main rotor, interactions and trim can require a full aircraft model, wind tunnel trim being only an approximation for flight.

There is the question of what the next generation of analysis will be called. Possibilities include HPC-Comprehensive Analysis, Universal Rotorcraft Analysis, 4-th Generation Comprehensive Analysis, or Multidisciplinary Analysis. For the purpose of this paper,

it will simply be called "Comprehensive Analysis." No doubt this would be too confusing for the near term, but a point is being made — this is what will be meant by comprehensive analysis in just a few years.

NEXT GENERATION

The next generation of rotorcraft comprehensive analysis will be enabled and driven by high-performance computing. The tool must be designed to use multiple cores: 100–10000 now, soon an order of magnitude (or two) more. All elements of the analysis must be parallel and scaleable. Experience already has shown that if some piece of the tool remains on a single processor, that piece eventually will be a bottleneck. Thus the tool requires distributed and possibly partitioned solution for all elements.

The tool should scale down as well, allowing execution on desktop machines, at least with the appropriate choice of model options. There must not be a separate code for the desktop environment. That environment will still be multiple cores however, at least 8 or perhaps 32 in not many more years.

The next generation comprehensive analysis will consist of the following components.
a) Case management tools for effect overall control of the process.
b) A geometry engine: the interface with the design and analysis environment, essential for productivity.
c) The integrated analysis: modular and scaleable.
d) Post-processing analyses: not just interfaces to other codes, but tools developed and used as part of the analysis.
e) Interfaces with all aspects of the design environment, including conceptual design and detailed design.

When large amounts of data are required from the integrated analysis, likely the post-processing tools will actually be co-processing, executed at the same time as the integrated analysis, but with a one-way flow of information.

GEOMETRY ENGINE

A geometry engine is required, driven by CAD systems and delivering the geometric descriptions required for the aerodynamic, structural, and control analysis (including discretization, grids and meshes). The geometry engine must also provide communication and standards needed for design and optimization, likely in terms of new data structures. Geometry conventions are needed at the system level, since modularity requires development of

interfaces between components of the analysis. These are system design issues, affecting the overall architecture, not just a matter of low level communication.

The aircraft description must be obtained from a CAD system, for exact representations of the aircraft, and for efficiency and throughput. This software tool will not drive the industry choice of CAD, so must accommodate all CAD systems in use by the community. There must also be a surrogate for simple or generic rotorcraft configurations — perhaps a simple Unix-based CAD program, with appropriate libraries of components.

A graphical user interface (GUI) is required as part of the geometry engine, for efficiency and throughput. The GUI will be modular, as required to handle multibody dynamics and finite elements, aerodynamic and structural grids, and flight controls. The GUI must be able to create and manipulate components, revise and repair grids.

The requirement for a geometry engine exists for the aerospace industry in general, so there should ultimately be industry-wide investment and solutions. Investment from the rotorcraft community is needed to ensure that rotorcraft-specific issues are addressed in the solution. Prototypes and surrogates for rotorcraft tools are needed to establish requirements and guide solutions. Well-chosen surrogates are essential while waiting for the industry-wide tool.

The current generation of comprehensive analyses and some post-processing tools must also use this geometry engine. This will require development of new interfaces for current codes.

HIERARCHY OF MODELS

A hierarchy of models is needed for efficiency and size: lower fidelity models are usually faster and smaller. A hierarchy of models is needed for accuracy and scope: lower fidelity models can be more accurate and more widely applicable (within limits of their development). The question is: how low in fidelity should the next generation analysis go? Should the next generation encompass all the technology of the current comprehensive analyses, such as lifting-line theory and beams, momentum theory and rigid blades?

There are numerous arguments for including low fidelity models in the next generation comprehensive analysis. Many problems do not require high fidelity for all disciplines, rather sometimes the task is only focused on aerodynamics or only on dynamics. Efficiency and understanding demand use of the simplest possible

models for each problem. The capability to effectively calibrate low fidelity models with high fidelity models in the same tool, with all other aspects of the solution identical, is desirable. Low fidelity models are needed for diagnostics, debugging, and validation. Backward compatibility with current generation comprehensive analyses is needed for user confidence and acceptance.

The argument for only high fidelity models in the next generation tool is the need to minimize requirements in order to define a bounded code development project, demanding reasonable resources and schedule. It is concluded here that all the arguments for low fidelity do not out-weigh the need to define a practical development project.

Thus the recommended requirement is that the next generation comprehensive analysis focus on high-fidelity models. Incorporation of low-fidelity models from current tools is not required.

Mitigating this position is the factor that current generation comprehensive analyses must be coupled to the geometry engine, so it is not necessary to replicate them in the next generation tool in order to directly compare results. In addition, some low-fidelity models can be expected to be implemented for other reasons. For example, structural models for rotor blades will include beams; rigid blade models are always available with multibody dynamics models; momentum theory may be used for trim algorithms or loose coupling; rotor wake models may be used in off-body wake-capture methods.

SUBSYSTEM REQUIREMENTS

In order to define the model requirements, rotorcraft subsystems will be considered: rotor and fuselage; propulsion system and engine; flight controls; acoustics; external interactions. Specific technology and models may be driven by certain subsystems, but because of the modularity of the analysis design all functionality is then available to all parts of the system.

Rotor Aerodynamics

Navier-Stokes solutions are required, for performance, drag, stall, and wake formation. A limitation will be turbulence modelling. There is definitely a need for better turbulence models, especially for unsteady flows. DES (detached eddy simulation) will be practical, and probably will be the standard model. Perhaps even LES (large eddy simulation) or DNS (direct numerical simulation) can be used, at least in limited domains.

There must be a method to deal with the wake of rotors. Wake capture with Navier-Stokes solutions may not be adequate at the time of the initial release of the next generation tool. Investment in research is needed to identify the best approach.

Post-processing requirements include entrainment, for brownout and whiteout computations.

Not required is formal lifting line theory (in place of an empirical model, or an actuator disk). While interesting theoretically, it would be a complicated digression from the primary requirements.

Physical approximations can be useful. Euler solutions bring reduced computation, but require drag estimation from lower fidelity models, such as lifting-line theory and airfoil tables. Wake (potential flow) models can be coupled with near-body Navier-Stokes solutions, for cases when wake-capture does not work or is too costly. However, integration of such wake models with the Navier-Stokes solutions must be done rigorously, fully consistent and fully coupled.

Geometric approximations can be useful, such as actuator disk and immersed boundary conditions.

Low fidelity models can be useful, including boundary element (panel) methods; lifting-surface theory; lifting-line theory; momentum theory. Wake models that can be used for lifting-line theory may be available for coupling with near-body Navier-Stokes solutions. Lifting-line theory may be required if use Euler solutions. Momentum theory may be needed for the trim solution with loose coupling.

However, usefulness alone is not considered enough justification for a requirement.

Rotor Structures

For blades, hub, and control mechanisms, the following are required: solutions of the exact structural dynamic equations with correct geometry (small strain is adequate); multibody dynamics, for exact kinematics and joints; three-dimensional structural models, including anisotropic and composite materials; beam finite elements.

Three-dimensional structural models are needed for correct modelling of coupling and load paths, and the non-beam-like parts of the system. They are needed for ends, short beams, open sections, transitions, joints — it is always a problem to make beam models fit all parts of a rotor blade. Research investment is needed to establish

the required resolution for high fidelity modeling of composites.

Beam finite elements are needed since rotor blades are usually slender structures. Beam elements involve one-dimensional analysis with two-dimension section properties from the geometry engine. Both isotropic and Euler-Bernoulli models are needed.

Post-processing requirements included detailed stress-strain solution, and damage tolerance assessment. Post-process analysis of higher-resolution substructures is usually the most effective approach for stress and strain calculation.

CFD and CSD

Reports of current research in rotorcraft simulation often describe CFD/CSD coupling. This terminology is really used just for symmetry. Usually CFD (often RANS) is coupled with the structural dynamics of current comprehensive analyses, so there is an unequal level of representation of the physics of the aerodynamics and the structure. Here it is concluded that the requirement is equal levels of representation, described as follows.

CFD solves the fundamental partial-differential equations of three-dimensional, unsteady fluid dynamics — with some approximations, the range of models including DNS, RANS, wakes, lifting-line theory, momentum theory.

CSD solves the fundamental partial-differential equations of three-dimensional, dynamic structural mechanics — with some approximations, the range of models including numerical solution, three-dimensional finite elements, beams, rigid bodies.

Rotors

Considering rotor configurations and the analysis/design tasks, the capability to model the following is required:
a) mechanisms, typically with multibody dynamics models;
b) dampers, smart materials;
c) active surfaces, trailing-edge flaps;
d) flow control;
e) icing formation and effects, including particle trajectory, ice growth, adhesion/shedding, grid revision.

Fuselage

Modelling fuselage aerodynamics requires Navier-Stokes solutions, for stall and drag; and Euler solutions, with the drag from lower fidelity models. Modeling fuselage structures requires three-dimensional structures for damping and nonlinearity; and modal or substructure models from existing codes (sufficient to represent linear structural dynamics).

Considering aircraft configurations and the analysis/design tasks, the capability to model the following is required:
a) circulation control tail boom;
b) slung loads;
c) landing gear;
d) stores, including launch and separation;
e) ground contact boundary conditions.

Crash analysis is not required, since it needs different models of the structure, involves ground and water contact, and has less requirement for aerodynamics. The capability for a large linear finite-element model is not necessary, since a modal or substructure model is an equivalent representation of the solution.

Propulsion System

A model of drive system structures (probably simplified) sufficient to account for coupling with rotor and airframe dynamics is required. Considering aircraft configurations and the analysis/ design tasks, the capability to model the following is required:
a) drive system loads;
b) interactions with rotors, for stability, loads, and flight dynamics;
c) control design.

Detailed drive system models, for calculations such as gear stress or windage, are not required.

Engine

Considering aircraft configurations and the analysis/ design tasks, the capability to model the following is required:
a) aerodynamic interactions with the rotors, at least the inlet and exhaust modelled, with engine mass flow;
b) engine dynamics and fuel control;
c) airframe and rotor flow field calculations for use in high fidelity engine aerodynamics analysis.

An integrated, high fidelity model of engine internal aerodynamics is not required, although the architecture of the code will likely make this a simple extension.

Flight Dynamics

Considering aircraft configurations and the analysis/ design tasks, the capability to model the following is

required in order for the next generation comprehensive analysis to deal with handling qualities:
a) aerodynamic interactions and aeroservoelasticity;
b) control system hardware and software;
c) pilot models.

An efficient and reliable solution procedure to couple airframe and rotors, involving both aerodynamics and structures, is required. Control systems introduce equations that are fundamentally different than those of aerodynamics and structures. This difference must be accommodated by the solution procedure. Research investment is required to establish how to scale such solution procedures in the high-performance computing environment.

Real time simulation capability is not required. Real time simulation always demands specialized and simplified models, compared to the highest fidelity models available at each era. Also, the flight control system model will not always be used for rotorcraft calculations.

Noise

Considering aircraft configurations and the analysis/ design tasks, the capability to model the following is required:
a) internal and external noise;
b) input for Ffowcs Williams-Hawkings codes, including geometry, loading, and quadrupoles.

The aerodynamic solution domain may have to encompass the acoustic far field, as an alternative to using quadrupoles in the FW-H code. Research investment is required to determine the most efficient way to model high-speed impulsive noise for all operating conditions, and to develop the required computation method.

Post-processing requirements include Ffowcs Williams-Hawkings codes, both for on-blade surfaces and permeable surfaces; and interior noise calculation, including drive train and airframe vibration contributions.

Broadband noise calculation, i.e. a stochastic solution, is not required. Noise propagation and scattering calculation capability is appropriate for post-processing.

Interactions with the Environment

Considering aircraft configurations and the analysis/ design tasks, the capability to model the following is required:
a) Ground, buildings, and ships, particularly for takeoff and landing conditions;
b) wind tunnels;
c) other aircraft, including formation flight and wake turbulence.

The analysis architecture must accommodate the input and the size of these problems. The analysis physics must encompass aerodynamic interactions and boundary conditions.

THEORETICAL BASIS

The analysis must be based on first principles for all disciplines, in terms of both physics and solution. Sound derivations and clear assumptions are required. Experience shows that modular architecture makes this requirement easier to fulfill.

All approximate or empirical models should have a path to first principles, as enabled in the future by hardware and algorithms. This is required for confidence in the models, accuracy of the solution, and growth of capability.

SOLUTION PROCEDURES

The analysis must perform with an integrated tool calculations of performance, blade loads, vibration, airframe and drive train loads, stability, flight dynamics and handling qualities, and noise. The principal computation tasks can be labeled trim, transient, and flutter.

The trim task solves for the control and aircraft mean state for specified steady operating conditions (an inverse solution), including hover, level flight, climb and descent, and turns.

The transient task integrates the equations in time from the trim state, for prescribed excitation, thereby modelling maneuvers.

The flutter task extracts and analyzes linear differential equations: time invariant or periodic equations, linearized about the trim state.

The solution procedures drive the architecture of the code. Required are rigorous mathematical and physical foundations for the procedures, including a theoretical basis for convergence. The solution procedure must be distributed and partitioned, for aerodynamics, structures, controls, and trim. Parallel solutions for aerodynamics are available. Parallel solutions for structures are new to rotorcraft applications. A suite of component solvers is likely.

Trim

The trimmed, periodic solution for the full aircraft is required, in free flight as well as in a wind tunnel. Even when the focus is on a single main rotor, interactions and trim can require the full aircraft model. Wind tunnel trim is only an approximation for flight.

The equilibrium solution, which is periodic motion, is required with low damped motion, such as the lag mode; with unstable motion, including flight dynamics and aeroelastic instabilities; and with high fidelity aerodynamics and structural models. For free flight, the operating condition must be extracted from the unsteady solution.

It is necessary to handle the main rotor and tail rotor configuration, for which the rotors have different periods. This requires an approximate solution, ignoring the aerodynamic and structural interactions at the wrong period. A solution over a very long period that covers both the main rotor and tail rotor periods can be obtained, but that is a very inefficient approach (unless the tail rotor speed is an integer multiple of the main rotor speed). Thus separate aerodynamic solutions for the rotors are needed, with harmonic structural motion.

Handling identical blades undergoing the same motion as a function of azimuth is necessary, for a significant increase in efficiency. Either the motion is obtained for only one blade over the complete period, or the motion of all blades over a fraction of revolution.

Loose coupling method for trim must be implemented: iterate separate solutions over the complete period for high fidelity aerodynamics (for fixed surface motion) and the CSD/trim (with prescribed aerodynamic loading). As generally only a small number of iterations is required for convergence, loose coupling is extremely efficient. With loose coupling, it is also easier to handle the cases of different rotor periods, and identical motions of all blades. Loose coupling is expected to be the standard method for trim. There is little reason to execute tight coupling for trim.

Transient

For the transient task, the prescribed input can consist of aircraft motion and controls; aircraft motion with calculated controls (inverse simulation); or controls with calculated aircraft motion. The time integration method requires rigorous mathematical and physical foundations, including a theoretical basis for convergence.

The occurrence of damage should be accommodated, including a change of configuration and change of connectivity of components.

Implementing a quasistatic solution is necessary. The time scales of maneuvers are typically much slower than the time scales of the rotor. A quasistatic solution will be more efficient, if the accuracy is acceptable.

Mission analysis is not required in the next generation comprehensive analysis.

Flutter

The flutter task is required for stability and response calculation, and control design. The task requires state models and order reduction, for both aerodynamics and structures.

The flutter task needs the same aircraft description and the same high-fidelity models as the trim and transient tasks. Nonlinear models are linearized about the trim solution, so the flutter and trim tasks must be accomplished in the same code.

DESIGN AND OPTIMIZATION

An uncertainty analysis is required, including estimation and propagation of errors. If optimization is implemented as a framework, it should be integrated with the comprehensive analysis framework. Gradient-based or adjoint optimization can be important for computational efficiency, hence gradient calculations can be required during the solution procedure.

A consideration of the uncertainty analysis and optimization in the design and development of the code architecture is required, which will be difficult to accomplish without at least a prototype or surrogate.

SOFTWARE CONSIDERATIONS

Software resources include the HI-ARMS project, and current generation comprehensive analyses. Conventions, conversions, and interfaces are required for motion representations, in addition to geometry. Software issues include language, object orientation, and data management.

A system design is needed that encompasses architecture, data structures, and communication. For good design, implementation, and maintenance, parallel information exchange should be kept at the top level module, with lower levels acting only on partitioned data; i.e. communications must be kept separate from computations. Software scales best if data is not collected

at interfaces, hence partitioning of interfaces should follow partitioning of the solution. Yet it is also necessary that load balancing be maintained for communications, just as for computations.

Regarding the user environment, either the solution procedures must have very robust convergence (for periodic motion and for trim), or automated help is required. There should be a system for file management and job control.

Modifications and additions to the software must be accessible to advanced users, not just to the primary developers of the tool.

While acknowledging that a high level of expertise will be needed, there must be effective training in the use of the tool.

CONCLUDING REMARKS

High-performance computing offers the opportunity for tremendous expansion of rotorcraft analysis and design capability. Experience with current tools makes clear what the requirements are for the next generation comprehensive analysis. As usual, rotorcraft tools demand the widest possible integration of disciplines, a fact that makes comprehensive analyses challenging and keeps the development interesting.

ACRONYMS

CAD	Computer-Aided Design
CFD	Computational Fluid Dynamics
CSD	Computational Structural Dynamics
DES	Detached Eddy Simulation
DNS	Direct Numerical Simulation
GUI	Graphical User Interface
HI-ARMS	HPC Institute for Advanced Rotorcraft Modeling and Simulation
HPC	High-Performance Computing
LES	Large Eddy Simulation
RANS	Reynolds-Averaged Navier-Stokes

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